

MITIGATING ATMOSPHERIC ANGULAR REFRACTION USING DUAL-WAVELENGTH PSEUDO-NONDIFFRACTING BEAMS: ADDRESSING THE ENGINEERING CHALLENGES

M. Dušek^{1*}, F. Barcet^{1,2}, P. Ray¹, J. Venc^{1,3}, A. Frausti^{1,4}, D. Mergelkuhl¹, J-Ch. Gayde¹

¹CERN, Geneva, Switzerland

²ETH Zurich, Zurich, Switzerland

³Charles University, Prague, Czech Republic

⁴ESGT, Le Mans, France

Abstract

Optical alignment systems relying on straight-line references, such as the Structured Laser Beam (SLB)-based systems, are inherently susceptible to atmospheric refraction. As an SLB propagates through air with a non-homogeneous refractive index distribution, variations in the refractive index cause the beam to deviate from its nominal path, introducing offset errors in the alignment reference. Although these effects can be substantially reduced by using a vacuum pipe, this approach involves significant experimental complexity. This paper discusses the ongoing development and engineering challenges of a dual-wavelength dispersometry method for mitigating angular refraction errors arising from variations in the refractive index of air, using 405 nm and 639 nm SLBs. Experimental results obtained over a 140 m propagation path in the CERN TT1 tunnel demonstrate that vertical refraction correction can achieve repeatability errors below 46 μm under controlled mechanical alignment conditions. However, systematic discrepancies observed along the horizontal axis, together with the results of post-realignment tests, highlight the system's high sensitivity to the initial setup alignment, which limits reproducibility. The paper evaluates the current performance constraints and outlines the key modifications for the further development and optimization of the system.

INTRODUCTION

Optical alignment systems that rely on straight-line references, such as the Structured Laser Beam (SLB) system, are inherently affected by atmospheric refraction variations [1]. Spatial and temporal variations in temperature, pressure, relative humidity, and carbon-dioxide concentration induce fluctuations and gradients in the refractive index of air. As the SLB propagates through this non-uniform medium, refraction causes the beam to deviate from its nominal straight-line trajectory, resulting in shifts of the beam centroid and, consequently, errors in the alignment reference.

In the SLB-based straight-line alignment system demonstrated in our previous work [2], an SLB establishes a straight reference line when propagating through a vacuum, where no atmospheric refraction occurs. In practical scenarios, however, operating long evacuated pipes introduces significant

mechanical and operational constraints. During free-air operation, the refraction-induced deflection of the laser trajectory must be actively compensated to recover the straight-line alignment reference. Previous studies on dispersometry have demonstrated that dual-wavelength beam tracking can correct for refraction-induced angular errors in geodetic instruments [3, 4]. This paper presents the engineering challenges encountered in developing a dual-wavelength dispersometry method, integrated into the SLB framework to correct for angular refraction.

Dispersometry

Since air is dispersive, its refractive index n depends on the wavelength λ , causing two co-aligned SLBs at different wavelengths to experience slightly different degrees of bending along the same atmospheric path. This will introduce a certain difference in position between these SLBs. Dispersometry leverages this differential bending to quantify and compensate for atmospheric refraction. In other words, when propagating through air, atmospheric dispersion causes the two beams to have different trajectories, resulting in a distinct spatial separation compared to propagation in vacuum. The physical shift in relative beam position ($\Delta s = R \cdot \Delta\beta$) directly encodes the dispersion angle $\Delta\beta$, with R being the propagation distance, which will be derived in the following text [3, 4].

For a horizontally stratified atmosphere where $n = n(y)$, Snell's law yields:

$$n(y) \sin \theta = \text{const}, \quad (1)$$

where θ is the local ray angle relative to the horizontal. Differentiating Eq. (1) gives the local path curvature:

$$\frac{d\theta}{ds} = -\frac{1}{n} \frac{dn}{dy}. \quad (2)$$

Integrating along a propagation path of length R yields the total angular deviation β :

$$\beta = - \int_0^R \frac{1}{n} \frac{\partial n}{\partial y} dr. \quad (3)$$

The difference in angular deviation between two wavelengths defines the dispersion angle:

$$\Delta\beta = \beta_1 - \beta_2. \quad (4)$$

* martin.dusek@cern.ch

Because both beams travel in an identical environment, the path-dependent atmospheric terms cancel out. Consequently, the absolute refraction angle β_1 affecting the primary reference wavelength can be determined directly from the measured dispersion angle:

$$\beta_1 = K(\lambda_1, \lambda_2) \Delta\beta, \quad (5)$$

where the atmospheric dispersion factor $K(\lambda_1, \lambda_2)$ is given by:

$$K(\lambda_1, \lambda_2) = \frac{n(\lambda_1) - 1}{n(\lambda_1) - n(\lambda_2)}. \quad (6)$$

By measuring the physical separation between the two beam centroids relative to their vacuum baseline, the corresponding angular divergence $\Delta\beta$ is obtained. Note that when implementing such a system, it must be taken into account that the laser trajectories will not be perfectly identical in vacuum. The system must first be calibrated by propagating in vacuum to establish a reference baseline for the positional difference between two SLBs, accounting for minor alignment offsets. Applying the correction obtained from Eq. (5) to the measured beam position removes the atmospheric bending error, recovering the true trajectory the beam would have followed in a vacuum.

METHODOLOGY

A dual-wavelength SLB generator was constructed using laser sources operating at $\lambda_1 = 405$ nm (Thorlabs PL255) and $\lambda_2 = 639$ nm (Thorlabs PL252). The experiments were conducted in the Transfer Tunnel 1 (TT1) at CERN. Refractive indices $n(\lambda_1)$ and $n(\lambda_2)$ were calculated using CiddorPy [5] based on direct measurements near the laser source of ambient temperature ($T \in [15^\circ\text{C}, 18^\circ\text{C}]$) and relative humidity ($\text{RH} \in [70\%, 90\%]$), alongside assumed baseline values for pressure ($P = 970$ hPa) and carbon dioxide concentration ($\text{CO}_2 = 450$ ppm). These environmental parameters yielded the corresponding theoretical scaling factors $K(\lambda_1, \lambda_2)$ for each experimental set.

The two laser beams were co-aligned using a dichroic mirror (Thorlabs DMLP425) into the SLB generator, with each beam path incorporating two steering mirrors (Thorlabs PF10-03-P01) to provide four degrees of freedom for alignment with respect to the optical elements. The generator consisted of a phase lens located close to the laser sources (Thorlabs LA1576-A) and a projection lens (Thorlabs LA1612-A). Lenses were positioned with their concave surfaces facing each other. The distance L_{PL} between the lenses was adjusted such that the beam diameter, measured between the first dark ring minima at a distance of 140 m, was approximately 8.5 mm for the red SLB and 8.3 mm for the blue SLB to fit on to a CMOS sensor (Basler acA4112-30uc).

The combined beam propagated through ambient air before passing through two steering mirrors (Thorlabs PF20-03-P01) to provide four degrees of freedom for alignment

into a 140 m long vacuum pipe terminated by optical windows. At a distance of 140 m, the arriving transverse profiles were captured directly using the CMOS sensor positioned behind the optical window. The spectral response and quantum efficiency of the sensor's red and blue channels enabled the two wavelengths to be almost completely isolated, with negligible cross-talk between them. Beam centroids were subsequently calculated using a gamma-corrected weighted center-of-gravity algorithm [6].

Baseline calibration was performed with the pipe evacuated to approximately 10^{-2} mbar, defining the baseline spatial separation of the two beams in vacuum. Measurements were subsequently repeated with the pipe vented to atmospheric air across the full 140 m path. Initial experiments indicated that open-air thermal turbulence near the source caused beam wander that propagated down the line. To stabilize environmental conditions, the SLB generator was enclosed in thermal insulation foam. Three independent repeatability validation tests were performed over three consecutive days. Additionally, reproducibility was evaluated by completely disassembling, remounting, and realigning the generator setup, followed by a calibration in vacuum and repetition of the atmospheric measurement sequence.

To evaluate the refraction compensation performance, the measured spatial shift of each beam between vacuum and atmospheric conditions was compared against the shift predicted by the dispersometer model. The effect of the net chromatic dispersion was determined by taking the difference between the relative beam separation measured in air and the baseline separation measured in vacuum. Multiplying this net dispersion by the scaling factor $K(\lambda_1, \lambda_2)$ yields the predicted refraction-induced shift. Subtracting this predicted shift from the actual physical displacement measured in air determines the residual correction error, validating whether measuring wavelength-dependent beam separation can successfully recover the vacuum reference position, which remains virtually unaffected by refraction.

RESULTS AND DISCUSSION

The values presented in the tables throughout this section are reported in μm as mean $\pm$ standard deviation (1σ), calculated across 150 frames recorded over 5 minutes per run. Table 1 presents the vertical axis evaluation across a three-day measurement campaign, establishing the baseline repeatability under consistent mechanical alignment.

Vertical atmospheric refraction caused downward beam deflections exceeding 3.4 mm over the 140 m path. By evaluating the change in beam separation between air and vacuum to determine the net chromatic dispersion, the predicted refraction shift was calculated using Eq. (6). The dispersometer model successfully corrected this downward bending, agreeing with the measured displacements to within residual errors between 6.5 μm and 45.8 μm . This corresponds to compensating for 98.7 % to 99.8 % of the total vertical refraction effect across all three validation runs.

Table 1: Vertical axis dual-wavelength refraction compensation at 140 m.

Parameter	Day 1	Day 2	Day 3
Red shift	3405.5	3586.5	3342.5
(Air – Vac)	± 16.9	± 17.4	± 19.1
Blue shift	3479.8	3665.5	3415.6
(Air – Vac)	± 19.4	± 19.9	± 17.1
Beam dispersion (Vac)	652.7	818.0	759.4
	± 6.9	± 9.4	± 5.3
Beam dispersion (Air)	726.9	738.9	832.6
	± 5.9	± 7.6	± 11.1
Net dispersion	74.2	79.1	73.2
<i>K</i> -factor	46.3	46.4	46.4
Predicted shift	3436.2	3671.8	3392.8
Measured shift	3442.7	3626.0	3379.0
Residual error	6.5	45.8	13.8

Table 2 presents the corresponding evaluation for the horizontal axis over the same three measurement campaigns.

Table 2: Horizontal axis dual-wavelength refraction compensation at 140 m.

Parameter	Day 1	Day 2	Day 3
Red shift	154.7	23.2	28.3
(Air – Vac)	± 16.4	± 18.9	± 17.4
Blue shift	125.9	53.3	74.0
(Air – Vac)	± 19.0	± 18.9	± 19.9
Beam dispersion (Vac)	636.4	706.1	711.4
	± 7.0	± 4.8	± 9.4
Beam dispersion (Air)	665.2	676.1	757.1
	± 5.9	± 7.5	± 7.6
Net dispersion	28.8	30.0	45.7
<i>K</i> -factor	46.3	46.4	46.4
Predicted shift	1333.7	1392.60	2118.2
Measured shift	140.3	38.3	51.1
Residual error	1193.4	1354.3	2067.1

The physical horizontal refraction was small, with the mean measured beam shift remaining under 140.3 μm across all runs. This behavior is expected because horizontal thermal gradients in underground tunnels are typically weak. However, minor variations in detected beam positions yielded net dispersions between 28.8 μm and 45.7 μm . Because $K \approx 46.4$, any sub-micrometre measurement noise or structural drift in centroid estimation is amplified more than 46-fold into the position correction. Consequently, applying the dispersion scaling factor caused the model to overpredict horizontal refraction shifts above 1.3 mm, resulting in residual errors between 1193.4 μm and 2067.1 μm .

Table 3 presents the results across both axes following the realignment, assessing the reproducibility. The results of the reproducibility study highlight the impact of mechanical

setup changes on dispersion measurements. Rebuilding the system fundamentally altered the relation between the measured beam displacements and the predicted refraction shifts derived from wavelength separation. On the vertical axis, where large physical refraction occurred (3532.3 μm), the dispersometer model predicted a shift of 3244.1 μm based on a net dispersion of 69.9 μm , yielding a residual error of 288.2 μm . Conversely, on the horizontal axis, the net dispersion dropped to 1.4 μm , resulting in a predicted shift of 64.97 μm that closely tracked the physical displacement of 96.6 μm with a residual error of 31.6 μm .

Table 3: Dual-wavelength compensation results for both axes after complete setup rebuild and realignment at 140 m.

Parameter	Vertical Axis	Horizontal Axis
Red shift	3497.3	95.9
(Air – Vac)	± 16.8	± 18.5
Blue shift	3567.2	97.3
(Air – Vac)	± 19.9	± 21.4
Beam dispersion (Vac)	366.5	18.9
	± 5.4	± 13.0
Beam dispersion (Air)	296.6	17.5
	± 6.1	± 8.6
Net dispersion	69.9	1.4
<i>K</i> -factor	46.4	46.4
Predicted shift	3244.1	65.0
Measured shift	3532.3	96.6
Residual error	288.2	31.6

This shift in model agreement across axes demonstrates the high sensitivity of wavelength-dependent separation to physical realignment, indicating that the orientation of the setup relative to the vacuum windows and the resulting optical deformation of the windows due to the change of pressure is likely the primary driver of these residual discrepancies. Evacuating the vacuum pipe introduces the optical windows to mechanical stress, causing slight flexure and chromatic wedge deflections during calibration. Because beam positions were monitored at a single detection plane at 140 m outside of vacuum, any artificial angular deflection at the exit window accumulates over the entire propagation distance.

Furthermore, because the dispersion scaling factor $K \approx 46.4$, any uncompensated sub-micrometre mechanical drift or optical disturbance is severely amplified in the final predicted position. Specifically, a centroid estimation error of just 1 μm in the net dispersion Δs produces a 46.4 μm shift in the predicted refraction correction.

CONCLUSION

This paper presented the development and engineering challenges of a dual-wavelength SLB dispersometry system for atmospheric refraction compensation over a 140 m path. Under stable mechanical alignment, the method demonstrated proof-of-concept performance, reducing vertical re-

fraction deflections exceeding 3.4 mm down to residual errors below 46 μm .

However, reproducibility analysis revealed critical vulnerabilities in practical implementation. Future work will focus on the coupling of both lasers into a single-mode fiber to guarantee identical launch trajectories and eliminate relative pointing jitter. Subsequent efforts will also address multi-point in-vacuum camera measurements at 2 m, 70 m, and 140 m to decouple window flexure from affecting the SLB trajectories.

Additionally, the theoretical dispersion factor K exhibits sensitivity to environmental fluctuations of ambient temperature, pressure, and relative humidity. In the present setup, temperature and humidity were measured at a single point along the propagation path, whereas barometric pressure and CO_2 concentration were assumed static based on nominal baseline values. Unmonitored spatial gradients or temporal drifts along the tunnel directly impact the achievable correction accuracy. For instance, an unmonitored path-averaged temperature variation of 1 $^\circ\text{C}$ results in $\Delta K \approx 0.1$. To eliminate this source of uncertainty, future developments will integrate environmental monitoring distributed along the 140 m propagation path to calculate path-averaged K -factors.

Finally, the performance of the system will be benchmarked against Wire Positioning Systems and Hydrostatic Leveling Systems.

ACKNOWLEDGEMENTS

The authors acknowledge the support of all CERN colleagues involved in this project.

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